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Multijunction Cells for Concentrators: Technology Prospects

Issue Study

Compiled by

R.R. Ferber
E.N. Costogue
K. Shimada

November 15, 1984

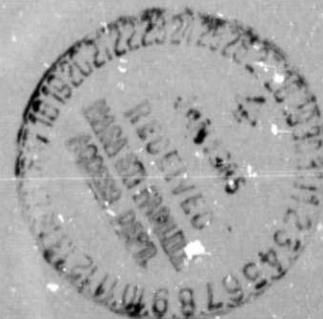
Prepared for

U.S. Department of Energy

Through an Agreement with
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Jet Propulsion Laboratory
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ABSTRACT

Development of high-efficiency multijunction solar cells for concentrator applications is a key step in achieving the goals of the U.S. Department of Energy National Photovoltaics Program. This report summarizes findings of an issue study conducted by the Jet Propulsion Laboratory Photovoltaic Analysis and Integration Center, with the assistance of the Solar Energy Research Institute and Sandia National Laboratories, which surveyed multijunction cell research for concentrators undertaken by federal agencies and by private industry. The team evaluated the potentials of research activities sponsored by DOE and by corporate funding to achieve projected high-efficiency goals and developed summary statements regarding industry expectations. Recommendations are made for the direction of future work to address specific unresolved aspects of multijunction cell technology.

PREFACE

The U.S. Department of Energy (DOE) National Photovoltaics Program objective is to develop photovoltaic (PV) energy systems that can be competitive with other grid-connected power-generating sources. As a result of several studies, the program has established a goal that the photovoltaic energy source must produce electrical energy at a 30-year levelized cost of \$0.15/kWh to be a viable widespread energy alternative for the nation. Two photovoltaic collector approaches have emerged with potential to achieve this goal: flat-plate collectors and concentrator collectors. The technical goals for these systems are listed below:

	<u>Flat Plate</u>	<u>Concentrator</u>
Collector efficiency	13% to 17%	23% to 29%
Collector cost	\$40/m to \$75/m ²	\$90/m to \$160/m ²

These goals can be achieved through the use of low-cost high-efficiency solar cells for the collectors. For flat-plate collectors, silicon ribbons, thin-film and thin-film multijunction cells having high efficiency are promising technologies for reduction of the cost of solar-cell material. For concentrating collectors, the most viable option is high-efficiency multijunction solar cells.

The DOE Five-Year Research Plan technical milestones for the high-efficiency multijunction concentrator cells are:

	<u>FY84</u>	<u>FY88</u>
Efficiency goals under concentrated sunlight	30%	35%
Multijunction cell area	≤1 cm ²	>1 cm ²

The Solar Energy Research Institute (SERI) and Sandia National Laboratories, Albuquerque (Sandia) conduct research projects to develop multijunction solar cell technologies that achieve the efficiency goals. To evaluate the probability that multijunction cells for concentrators can achieve high efficiency, an issue study was initiated by the Jet Propulsion Laboratory Program Analysis and Integration (PA&I) Center. The objectives were to:

- (1) Identify federal agencies' [National Aeronautics and Space Administration (NASA), DOE and Department of Defense] objectives and goals for multijunction cells for concentrators and related technologies for space and terrestrial applications.
- (2) Identify industry research activities and expectations.
- (3) Summarize status, issues, problems, trends, and research direction for each.

- (4) Evaluate potential for research activities to achieve projected efficiencies.

An industry survey was conducted and data were collected on the technology status, trends and issues. An analysis of the data was made to identify prospects and future research directions. The PA&I study team, with the assistance of SERI and Sandia team members, has reviewed the collected data on multijunction cells for concentrators and, based on the opinions and comments of the researchers interviewed and assuming that adequate funding will continue, arrived at the following summary statements:

- (1) Higher than 25% efficiency in multijunction cells may be achieved soon at moderate concentrations; when these cells are optimized, they could achieve 30% efficiency.
- (2) Within two years 30%-efficient multijunction cells for concentrators may be achieved, probably with a three-terminal or four-terminal configuration.
- (3) It appears that 35%-efficient multijunction cells for concentrators are still quite far off; they will probably not be achieved until the late 1980s or early 1990s and will require innovation (e.g., a unique structure with near-ideal materials and possibly three junctions).
- (4) It is expected that III-V material quality is the key to success for monolithic cells. Continued and expanded research on materials impurity effects is needed.
- (5) Difficulties have been experienced in fabricating good tunnel junctions. According to some experts, III-V materials tunnel-junction formation will require further technology advancement to achieve a doping concentration as high as 10^{19} . There are also some concerns that the series resistance of a tunnel junction is too large for high-concentration (>500X) use.
- (6) Source-material purity problems still hinder the assessment of growth chemistry.
- (7) Measurement standards and procedures for multijunction devices are badly needed to allow a uniform comparative performance evaluation.
- (8) The organo-metallic chemical vapor deposition (OMCVD) process is presently considered to be the best low-cost process for mass production of multijunction cells. Liquid-phase epitaxy (LPE), although less flexible than OMCVD and therefore less suitable, has been used successfully to produce high-efficiency GaAs cells with good yield, and is still a viable option for multijunction concentrator cells.

To achieve the objectives and goals of the DOE photovoltaic program for multijunction cells for concentrators, the team members identified the following key research areas to achieve high-efficiency cells:

- (1) Improved quality and understanding of ternary and quaternary III-V compounds.
- (2) Precision control of crystal-growth processes.
- (3) Research in materials, components, and measurement techniques and standards.
- (4) Device research involving modeling, advanced measurements (lifetimes, recombination current, etc.) and processing to optimize the solar cell for each III-V alloy.

These key research areas require a multidisciplinary team that includes industry, university, and DOE field center experimenters. Specific research tasks that require further development are listed below, not in order of priority.

- (1) Materials research to establish purity and crystalline defect limit requirements.
- (2) Assessment of the electronic effects of material impurities and defects.
- (3) Research on source-material purity requirements.
- (4) Assessment of the effects of dopant diffusion and complexing with other impurities and crystalline defects.
- (5) Development of low-loss tunnel junctions or other appropriate ohmic contacts between monolithically stacked p-n junctions.
- (6) Research on reaction chemistry during OMVCD growth.
- (7) Research to provide the necessary analytic tools needed to scale up crystal-growth processes for quantity production with acceptable yields.
- (8) Development of satisfactory lattice-matching interlayers to minimize crystalline imperfection.
- (9) Fabrication of monolithic heterostructures, using materials not matched in lattice constants.
- (10) Development of measurements for accurate evaluation of comparative performance and for device characterization.
- (11) Development of modeling capability for single-junction and multijunction devices.
- (12) Research on device processing, e.g., multilayer optical coatings, metallization, and cell interconnects.

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SECTION I

OBJECTIVES AND APPROACH

To achieve large-scale deployment of photovoltaic (PV) systems, the PV power technology must be advanced so that solar cells, modules, and arrays become efficient, low-cost energy converters. With the use of high-efficiency, multijunction, multiband-gap cells, concentrator arrays have the potential for conversion efficiencies higher than 30%. Maximum efficiency of single-junction cells depends primarily on the energy gap of the semiconductor that absorbs the solar photons. For single-junction cells, the highest theoretical AM1 efficiency for energy gaps between 1.45 and 1.5 eV is about 28% at an operating temperature of 28 C. The GaAs (gallium arsenide) cells have a measured one-sun efficiency of 21% to 22% with a bandgap of about 1.43 eV. For silicon cells with a bandgap of 1.1 eV, the calculated maximum conversion efficiency is about 25% at AM1, and silicon solar cells with efficiencies of 19% have been reported. The conversion efficiency decreases with increasing operating temperature, especially for a low band-gap material such as silicon.

Although small incremental increases in efficiency can still be expected as refinements are made to existing cell designs, efficiencies above 30% can only be achieved through the use of multijunction cells. In such cells, each junction will convert a fraction of the incident sunlight wavelengths into electricity. By dividing the solar spectrum into energy segments and making each spectrum segment incident upon a cell with appropriate optimal conversion characteristics, great improvement in conversion efficiency can be expected. Combining outputs of the cells can result in a multijunction cell with efficiency in the range of 30% to 35% under concentration.

A. THE NATIONAL PHOTOVOLTAICS PROGRAM

The Department of Energy (DOE) National Photovoltaics Program has long-term technical goals for concentrator collectors:

- (1) A collector efficiency of 23% to 29%.
- (2) A collector cost of \$90/m² to \$160/m².
- (3) A system life expectancy of 30 years.

The collector efficiency goal of 23% to 29% can only be realized with multijunction cells having an efficiency in excess of 26% to 32%. The Photovoltaics Program Five-Year Research Plan objectives for multijunction cells are:

- (1) 30% efficiency for an area of ≤ 1 cm² by September 1984 (not achieved on schedule).
- (2) 35% efficiency for an area of > 1 cm² by 1988.

Both the Solar Energy Research Institute (SERI) and Sandia National Laboratories (Sandia) conduct research for the development of multijunction cells. The emphasis of the SERI project is on materials research to improve the properties of the active semiconductor layers; the Sandia efforts are directed toward improving the quality of solar cells using the best available materials.

B. ISSUE STUDY

To assess the technology status for multijunction cells and the prospects for achieving the Five-Year Research Plan milestones, an issue study was organized by the Jet Propulsion Laboratory (JPL) Photovoltaics Analysis and Integration (PA&I) Center. The object of the study was to review multijunction research activities and evaluate the probability of achieving the projected goals of the plan for 30% efficiency by 1984 and 35% efficiency by 1988. Specific objectives of the issue study were:

- (1) To identify activities and plans of agencies such as DOE, the National Aeronautics and Space Administration (NASA) and the Department of Defense (DOD).
- (2) Identify industry activities and expectations.
- (3) Identify major problems and/or show stoppers, if any.
- (4) Evaluate the potential for multijunction cells to achieve projected high efficiencies.

A study team was formed with participation from both the SERI and Sandia research centers. The team members were as follows: from the PA&I Center, R. Ferber (study leader), E. Costogue, and R. Shimada; from SERI, J. Benner and E. Witt; from Sandia, D. Arvizu and J. Gee.

The approach that the team adopted to conduct the study is outlined below:

- (1) Summarize multijunction R&D activities sponsored by SERI and Sandia.
- (2) Summarize multijunction-related R&D sponsored by DOD and NASA.
- (3) Summarize the technology bases in foreign countries (Japan, Europe).
- (4) Summarize the technology base in domestic industry.
- (5) Review the data.
- (6) Analyze the data.
- (7) Issue a report on the findings.

SECTION XI

FEDERAL AGENCY OBJECTIVES, RESEARCH ACTIVITIES AND RESOURCE ALLOCATIONS

Data from federal-agency-sponsored multijunction cell research, as well as related technology, have been obtained from published annual operating plans, contractor review program reports, and from interviews conducted by the Photovoltaics Analysis and Integration Center. The agencies involved in multijunction research are the U.S. Department of Energy (DOE); the Solar Energy Research Institute (SERI); Sandia National Laboratories (Sandia); the U.S. Department of Defense (DOD), Wright Patterson Air Force Base; and the National Aeronautics and Space Administration (NASA), Lewis Research Center.

A. SOLAR ENERGY RESEARCH INSTITUTE, GOLDEN, COLORADO (DOE)

The information obtained from the FY 1984 Annual Operating Plan (AOP), the DOE Five-Year Research Plan, and the Progress Review Meeting publications is summarized below.

1. Objectives

Research on solar cell designs and materials with the objective of achieving the maximum attainable photovoltaic conversion efficiencies. This research is directed toward laboratory demonstrations of solar cells of greater than 30% efficiency under concentrated sunlight (greater than 100X) and thin-film solar cells with one-sun efficiencies of 17% to 20%.

2. Research and Development Plan

High-Efficiency Concepts Tasks; J.P. Benner, Manager.

a. Task 2.35¹, High-Efficiency Concepts.

Contracts:

Massachusetts Institute of Technology Lincoln Laboratories		
1/18/84 - 12/31/84	\$500K)	} (Not concentrator cell contracts)
Spire		
3/15/84 - 4/14/85	\$421K)	
Varian		
1/22/84 - 1/21/85	\$420K	
Chevron		
4/27/84 - 4/26/85	\$500K	

¹ SERI AOP task number.

Task Goals: Improve the quality of ternary and quaternary III-V compounds for use in multiband-gap concentrator cells. Identify and minimize the effects of various types of crystalline defects in GaAsP, AlGaAs, GaInAs, GaAsSb, AlGaAsSb, and AlGaInAs.

b. Task 2.222,² III-V High-Efficiency Cells, In-House Activities.

In-house efforts of 5.5 man yr (\$615 K) leading to the development of multijunction solar cells; this is specifically to build a GaAsP/Si cascade cell containing a GaAs/GaP superlattice and involves the following activities:

- (1) Research on thin-film materials for multijunction devices and device fabrication techniques that are complementary to subcontracted and outside independent research.
- (2) Demonstration of the capability of organo-metallic chemical vapor deposition (OMCVD) to make efficient shallow homojunction cells.

B. SANDIA NATIONAL LABORATORIES, ALBUQUERQUE, NEW MEXICO (DOE)

Information obtained from the FY 1984 AOP is summarized below.

1. Objectives

Research the performance potential of advanced semiconductor devices to be assembled into mechanically stacked multijunction cells capable of achieving high efficiency under concentrated sunlight.

2. Research and Development Plan

Task 4.2,³ Advanced Devices; J. Gee, Manager.

a. Contracts

Varian Associates	\$175 K	Total funding for 12-month contract
Hughes Research	232 K	
Spire Corp.	100 K	

Contract Objectives: To design and fabricate a high-efficiency, wide-band-gap cell to be used as the top cell for a mechanically stacked two-junction cell. Three approaches are under investigation: (1) AlGaAs on GaAs substrate by

²SERI AOP task number.

³Sandia AOP task number.

OMCVD, (2) AlGaAs on GaAs by liquid phase epitaxy (LPE), and (3) AlGaAs on Ge substrate by OMCVD. In each case the growth substrate is removed and the resultant thin AlGaAs cell is to be stacked on a red-enhanced silicon cell.

b. In-house Activities

Research and development on a AlGaAs and InGaAs monolithic, strained layer superlattice interlayer, two-junction, three-terminal cell by molecular beam epitaxy (MBE).

c. LEWIS RESEARCH CENTER, CLEVELAND, OHIO (NASA)

Lewis Research Center is the NASA organization responsible for solar-cell research. Information on work there was obtained from discussions with H. Brandhorst and H. Curtis of LeRC on February 28, 1984, and is summarized below:

1. Objectives

The NASA long-range objective is to develop a multijunction cell that is 30% efficient with AMO at 100X, 80°C. No time schedule has been announced.

2. Research and Development Plan

Contracts totalling \$250 K are with Massachusetts Institute of Technology Lincoln Laboratories and Varian Associates. The latter is a three-year contract that is likely to be renewed at the end of the third year.

Contract efforts are directed toward three-junction, two-terminal monolithic cells. The final product of the present Varian contract may be three-terminal and mechanically stacked.

Planned Cell Configuration

-----	}	1.95 to 2.0 eV, AlGaAs
-----		MIC ² interconnect or tunnel junction
-----	}	1.43 eV GaAs
-----		Tunnel junction or Ge interlayer
-----	}	1 to 1.15 eV GaInAs

P dopant: Mg rather than Zn

N dopant: Se, Si, or Te; a slow-diffusing dopant is required.

A tunnel-junction interconnect between the bottom and the middle cell is proposed. In-house efforts are aimed at an operational, computer-controlled, OMCVD reactor for thin-film depositions. The following comments were offered by LeRC regarding multijunction cell technology status:

- (1) A mechanically stacked cell with 20% to 25% efficiency (AMO) is achievable first.

- (2) Lattice match is not necessary, even for monolithic devices.
- (3) More material research is needed on impurity effects and the defects in III-V compounds.
- (4) LeRC is interested in the Hughes development efforts for GaAs cells using liquid-phase epitaxy (LPE).
- (5) LeRC is aware of ASEC future production of GaAs space cells and wants ASEC to try Varian's developed AlGaAs caplayer technology for the AlGaAs window and contacts.

Other comments:

H. Brandhorst believes that the present total government R&D funding of about \$3 M is too low to cover adequately all research options for high-efficiency multijunction cell technology that may be applicable to concentrators. He believes that \$3.5 to \$4 M/yr is the better level and he recommends the drafting of an overall multi-agency multijunction cell research program plan. The plan should be coordinated among all government agencies with barriers and options clearly identified and defined.

The Cleavage of Lateral Epitaxial Film for Transfer (CLEFT) process is considered by H. Brandhorst to be a backup to the monolithic approach. CLEFT cell handling and production are difficult and it is at least 10 to 15 years away from being a practical process. Federal funding is mainly directed to support continued creativity at Lincoln Laboratories rather than to a near-term device.

The OMCVD is expected to be the best low-cost process for mass production. NASA strongly endorses concentrator technology for space because of the "plug-in" cell technology capability.

It is estimated that space GaAs concentrator arrays will be operational in three to four years. Advanced cells could be plugged into later versions of the space concentrator. H. Brandhorst believes that interconnect technology and antireflective coating research for concentrator arrays are not currently receiving attention and are badly needed.

He endorses the new DOE program direction for high efficiency followed by low-cost emphasis. He also thinks that the United States is putting too much emphasis on II-VI thin films. Because there is substantial industry investment in this area, he says this research should be reduced or eliminated to allow more emphasis on the III-V material and device research. He pointed out the strong need for materials research similar to the silicon impurity studies by C.T. Sah Associates and Westinghouse Electric Corp.

D. WRIGHT PATTERSON AIR FORCE BASE, DAYTON, OHIO (DOD)

Wright Patterson is the U.S. Air Force center for solar cell and array research. Information obtained in discussions at Wright Patterson on March 8,

1984, is summarized below. P. Rahilly was initially interviewed and J. Wise later joined the discussions.

1. Objectives

The long-range objective is high efficiency with the most critical requirement being highest possible "end-of-life" performance. The target for this is a 30% efficiency (AM0), one sun cell by 1990 and beyond, using a three-junction cell structure.

The near-term objective is for two-junction cells of 25% efficiency (AM0), 1 sun.

2. Research and Development Plan

The activities are as follows:

- (1) A Hughes contract for research on a AlGaAs-GaAs multijunction cell with a tunnel junction interconnection will end in March 1985. This effort should demonstrate a three-terminal or four-terminal monolithic multijunction device using LPE growth.
- (2) A Chevron contract is being negotiated.
- (3) A Lockheed contract has been let for GaAs array development using 50,000 $2 \times 4 \text{ cm}^2$ GaAs cells to be manufactured by ASEC.
- (4) A JPL radiation damage assessment contract for GaAs is under way.
- (5) Advanced concentrator development activities will begin in the near future.
- (6) A TRW contract for 100X Cassegrainian concentrator development is in effect.
- (7) A General Electric contract for a small concentrator feasibility study.
- (8) A General Dynamics contract for linear parabolic concentrators (SLATS) with joint Navy, NASA, and Air Force support.
- (9) Contracts were recently completed with the Research Triangle Institute and Varian Associates on thin-film cells.

P. Rahilly offered the following comments regarding multijunction cell technology:

- (1) Multijunction cell technology will be needed for future military missions. Some missions cannot be flown with Si cells, and GaAs cell performance is marginal for them.

- (2) Mechanically stacked cells are the most promising in the near term. GaAs on Ge should be suitable for early monolithic cells.
- (3) A 30%-efficient AMO multijunction cell at one sun using three junctions will not become available until about 1990.
- (4) Improved III-V material quality is expected to be the key to success for monolithic cells; additional materials research is needed.
- (5) Array cost is an important factor for repetitive missions.

E. FEDERAL AGENCY RESOURCE ALLOCATIONS

Federal resource allocations for multijunction cell research are shown in Table 1. The table lists allocations, organizations funded to conduct the research, and the technology areas covered. Based on this information, about \$3.0 M in federal resources for FY84 are allocated for multijunction research, with the majority of the funds provided by DOE. It should be noted that not all of the resources listed are for research on multijunction cells for concentrators.

Table 1. Multijunction Cell Technology, Contractor and Agency Funding

CONTRACTOR	III-V Si	VAC OMCVD	OMCVD	LPE	CLEFT	STACK	3J.	3T.	TUNNEL	METAL INCONN.
FY84 Funding VARIAN										
\$150K - NASA			LEWIS				LEWIS		LEWIS	LEWIS
420K - DOE			SERI							SERI
159K - DOE			SANDIA			SANDIA				
MIT/LL										
\$500K - DOE	SERI		SERI		SERI	SERI				
100K - NASA					LEWIS	LEWIS				
CHEVRON								SERI		
\$250K - DOE		SERI								
100K - USAF		USAF								
HUGHES										
\$460K - USAF				USAF					USAF	
168K - DOE				SANDIA		SANDIA				
SPIRE										
\$430K - DOE	SERI		SERI							
100K - DOE			SANDIA			SANDIA				
RTI										
() - DOE			SERI						SERI	
() - USAF			USAF						USAF	
() FY83 Funding										

GOVERNMENT FUNDING FOR MULTIJUNCTION CELL RESEARCH THAT CAN BE APPLIED TO
CONCENTRATOR COLLECTORS IS APPROXIMATELY 3.00M BROADLY BASED, 2.15M DOE,
560K A.F., 250K NASA

SECTION III

RESEARCH STATUS

This section reviews the industry survey data collected to assess the status of multijunction cell research for concentrators, the problems and progress achieved, and prospects for achieving the DOE program goals as viewed by the researchers.

The organizations surveyed are either conducting research for multijunction devices for concentrators or were involved in research related to multijunction cell technology. Foreign multijunction research is also described briefly. Those surveyed were:

Hughes Research Laboratories, Malibu, California

Chevron Research Laboratories, Richmond, California

Varian Associates, Palo Alto, California

Research Triangle Institute, North Carolina

Massachusetts Institute of Technology Lincoln Laboratories, Boston, Massachusetts

Spire Corp., Bedford, Massachusetts

Applied Solar Energy Corp., City of Industry, California

Rockwell International, Thousand Oaks, California

For survey details and information collected, see Appendix A.

A. HUGHES RESEARCH LABORATORIES, MALIBU, CALIFORNIA

Project sponsors for the work are the U.S. Air Force and Sandia. Work is being done for Sandia on an AlGaAs/Si mechanical-stack, four-terminal multijunction cell and for the USAF on an AlGaAs/GaAs monolithic two-junction cell.

Progress is described:

- (1) Eighty single-junction AlGaAs/GaAs heteroface cells (2 x 2 cm) can be produced per run with good yield by pilot production LPE machines.
- (2) AlGaAs/GaAs single-junction concentrator cells (0.5 cm diameter) made for LeRC achieved >23% efficiency at 100X, AM1 (Sandia measurement of 25% later corrected downward).

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- (3) Good ohmic contact was achieved using Au-Zn combination on AlGaAs.
- (4) Precise etching has been developed for thin film device fabrication.

Comments:

- (1) Thin AlGaAs top cell fabrication on a sacrificial substrate should be achieved in 1984.
- (2) Difficulties in fabricating good tunnel junctions required for two-terminal multijunction cells are stressed by Hughes (Kamat) with the observation that alternative interconnect schemes are available and are likely to be used by Hughes.
- (3) Two-terminal or four-terminal 25%-efficient AM1 monolithic cells are feasible in 1984.
- (4) Two-terminal 30%-efficient AM1, multijunction cells are still a couple of years away, and achievement of 35% is several years beyond that.
- (5) The effects of material impurities are not well understood and present a major problem. More research funding is needed in this area.
- (6) Performance measurement and efficiency comparisons of thin-film devices for multijunction cells have been a problem because of the lack of standard measurement procedures and instrumentation.

B. CHEVRON RESEARCH LABORATORY, RICHMOND, CALIFORNIA

Work involves GaAsP/GaAsSb, two-junction three-terminal devices using two GaAs transition layers, with a pn-np structure. The work is sponsored by the U.S. Air Force (USAF) and SERI. Progress is described:

- (1) A vacuum OMCVD system produces films of high uniformity with efficient use of source material.
- (2) A monolithic GaAsP on GaAsSb cell achieved 22% efficiency using Zn p dopant; top-cell-18.3%, bottom-cell-3.6%. Mg doping is expected to improve the efficiency of the bottom cell to 6.5%.
- (3) Mg p dopant is being investigated for use in place of Zn dopant to increase the p-doping concentration of the GaAsP layers with increased phosphorus incorporation. Mg doping also eliminates unwanted Zn diffusion during cell processing and Zn "memory" effects.
- (4) Purification of the organo-metallic Mg dopant source material is necessary before its use.
- (5) GaAsP (1.65 eV) cells have been fabricated with 17% efficiency at 130X.

Comments:

- (1) Purification of source material is important. Purification of both Zn and Mg is ongoing at the Chevron facilities.
- (2) The extent of impurity effects on cell performance has not been well documented for each impurity species.
- (3) There is difficulty in measuring performance of devices because no standard cell or measurement approach exists.

C. VARIAN ASSOCIATES, PALO ALTO, CALIFORNIA

Work is performed under the sponsorship of Sandia, NASA, USAF, and SERI. Focus is upon III-V ternary compounds used in conjunction with a strained-layer superlattice interlayer and MIC² interconnect techniques.

A progress summary:

- (1) OMCD technology developed for thin-film growth of III-V compounds, with excellent uniformity of deposition and reproducibility of growth.
- (2) AlGaAs/GaAs single-junction heteroface concentrator cells made for Sandia have demonstrated 24% efficiency at 400X. Two cells measured at SERI were reported to have efficiency greater than 20% at 1 sun. Each had a band gap of 1.64 eV, near the optimum for the top cell of AlGaAs/GaInAs multijunction cells. One cell has an area of 4 cm².
- (3) An AlGaInAs quaternary-graded layer was developed for subcell layers in tandem III-V ternary cells.
- (4) Mg has been shown to be the preferred p dopant.
- (5) Testing of AlGaAs/InGaAs cells with MIC² technology is under way.
- (6) Further development of GaAsP cell material is being done.
- (7) Thin AlGaAs films are being fabricated for use in mechanically stacked multijunction cells.

Comments:

- (1) Strained layer superlattice requires further development to provide lattice match and internal cell contact.
- (2) Mechanically stacked multijunction cells, 25% efficient at concentration, appear achievable in the near term.
- (3) Materials purity is of great concern; Varian is purifying incoming materials.
- (4) A 30%-efficient multijunction cell is expected to be available by 1985, with 35% efficiency at least five years away.

D. RESEARCH TRIANGLE INSTITUTE, RESEARCH TRIANGLE PARK, NORTH CAROLINA

Project sponsors are SERI and the USAF. The work involves AlGaAs/GaAs graded band-gap, monolithic, two-terminal cells, patterned Ge tunnel junctions, and OMCVD.

Progress is summarized:

- (1) Epitaxial growth of AlGaAs/GaAs has already been demonstrated.
- (2) Conformal epitaxial growth of AlGaAs on patterned Ge stripes has also been demonstrated.
- (3) Computer analysis of a practical AlGaAs/GaAs cell structure, indicated that one-sun efficiency of 25%, AM1.5, and 500-sun efficiency of 30%, AM1.5, are achievable.

Comments:

- (1) Epitaxial growth of AlGaAs on oxidized AlGaAs is a new technology.
- (2) A greater level of material research is needed to achieve good III-V solar cells.
- (3) Measurement standards are needed for thin-film multijunction devices.
- (4) 30% AM1 efficiency multijunction cells can be expected within a couple of years; 35%-efficient cells are at least five years away.

E. MASSACHUSETTS INSTITUTE OF TECHNOLOGY LINCOLN LABORATORY,
BOSTON, MASSACHUSETTS

Work centered upon AlGaAs/Si or GaAsP/Si cells grown with OMCVD and a CLEFT-grown AlGaAs top cell for mechanically stacked cells. Project sponsors for this work are SERI, USAF and NASA.

Progress:

- (1) CLEFT technology is being developed for AlGaAs, GaAs, and GaAsP.
- (2) One-sun efficiency at 16.9% AM1 has been demonstrated with $\text{Al}_{0.2}\text{Ga}_{0.8}\text{As}$ shallow homojunction cell.
- (3) A 15% AM1 efficiency has been demonstrated with a $\text{GaAs}_{0.75}\text{P}_{0.25}$ cell.
- (4) 20% efficiency has been achieved with a GaAs/Si mechanically stacked cell.
- (5) GaAs has been grown epitaxially on Si.
- (6) Defect densities on heteroepitaxial GaAs on silicon have been reduced to $10^4/\text{cm}^2$.

Comments:

- (1) For multijunction cells, three junctions are the upper practical limit.
- (2) Research priority should continue to be for devices, with moderate increase in funding recommended. Significant increase is recommended for materials R&D if any III-V funding increase occurs.
- (3) Four-terminal 30%-efficient AM1 multijunction cells are feasible in the near future; 35% multijunction cells are at least a few years away.

F. SPIRE CORP., BEDFORD, MASSACHUSETTS

Work is sponsored by SERI for AlGaAs, GaAsP and GaAs on Si or Ge for two-terminal or four-terminal structures using OMCVD.

Progress is summarized:

- (1) An OMCVD AlGaAs/GaAs cell on GaAs substrate achieved a one-sun AM1.5 efficiency of 20.5%, with 22% expected in the near future.
- (2) A GaAs cell on Ge substrate achieved 15% efficiency.
- (3) An ion-implanted single-crystal Si cell achieved one-sun AM1 efficiency of 18%.
- (4) Heteroepitaxial growth has been achieved for GaAs and AlGaAs directly on silicon and on germanium-coated silicon.

Comments:

- (1) Mechanically stacked 25%-efficient cells will be achieved in three to four years.
- (2) Spire is also developing amorphous silicon multijunction cells for flat-plate applications.
- (3) Standard measurement procedures and instrumentation are needed.

G. APPLIED SOLAR ENERGY CORP., CITY OF INDUSTRY, CALIFORNIA

The GaAs efforts are sponsored by USAF, LeRC and Sandia, and are aimed at a high-efficiency GaAs cell for flat-plate space PV arrays and a high-efficiency silicon concentrator cell.

Progress is summarized:

- (1) Silicon cell efficiencies higher than 20% (100X) have been demonstrated by optimizing cell surface properties, including AR coatings, passivation, and grid structures.

- (2) Efficiency of 16.9% (AMO), 20% (AM1) 1-sun has been demonstrated with 2 x 2-cm GaAs cells produced by an OMCVD process for USAF.
- (3) ASEC is capable of producing 1,000 2 x 4-cm AlGaAs/GaAs cells per week at present by OMCVD with a good mechanical yield (80%).

Comments:

- (1) Reduction of Ga and As source material cost is required to achieve economic viability for GaAs cells.
- (2) Source materials may become a problem. At a production rate of 5,000 cells per week, ASEC could be using the entire world supply capability for pure growth source materials; however, Ga elemental availability is not considered to be a problem.
- (3) Bridgeman and Cz growth control of GaAs is inadequate to ensure a low dislocation density supply of polished wafers. ASEC believes that they need less than 5,000 dislocations per cm^2 and would ultimately like much lower dislocation counts. It is difficult now to get wafer shipments of less than 10,000 dislocation density.

H. ROCKWELL INTERNATIONAL, THOUSAND OAKS, CALIFORNIA

Rockwell has no solar cell work at the present, but is involved in GaAs and other electronic device development for DOD such as infrared sensors, GaAs high-speed semiconductor devices, GaAs lasers, detectors and InP lasers.

Comments:

- (1) Monolithic multijunction cells interconnected by tunnel junctions are difficult to fabricate.
- (2) Ge tunnel junctions are relatively easy to make.
- (3) Advanced material research is needed in III-V compounds.

I. JAPAN

Japanese activities in multijunction cell research are for flat-plate collectors only. A small silicon-based concentrator collector development program is in progress.

Mitsubishi Electric Corp. is developing a tandem-type solar cell fabricated with a-Si:H and a-SiGe:H films. By combining n-i-p a-Si:H cells and a-SiGe:H cells, two kinds of tandem cells were fabricated: (1) a two-junction stacked cell composed of an n-i-p a-Si:H cell and an n-i-p cell using an intrinsic a-SiGe:H film, and (2) a three-junction stacked cell composed of two a-Si:H cells and an n-i-p cell using an a-SiGe:H film. An efficiency of 8.5% was achieved with a three-junction stacked cell. Cell performance improvement research is continuing. Mitsubishi has a high volume (200-cell runs) production of single-junction 2 x 2 cm GaAs cells, with an average efficiency of 17.5% AMO and maximum efficiency of 19.3%. They are also working with the OMCVD process for cell formation.

production of single-junction 2 x 2 cm GaAs cells, with an average efficiency of 17.5% AMO and maximum efficiency of 19.3%. They are also working with the OMCVD process for cell formation.

Osaka University, Sanyo, and Sharp/ECD are also developing tandem-type solar cells with a-Si:H and a-SiGe:H. The results so far have been similar to those of Mitsubishi Electric, with efforts continuing to improve efficiency. Sanyo reported achieving 11.5% 1 cm² cell efficiency in September 1984.

J. EUROPE

Small research efforts are being conducted on multijunction cells for terrestrial concentrators or for space use by ENI in Italy and by Photo Industries in France. Information on the work is sketchy and no device performance results are yet available. There are also unconfirmed reports that the USSR is developing graded band-gap cells.

K. TECHNOLOGY COMPARISON MATRIX

Data collected for the study of the research activities have been used to develop a technology comparison matrix for four key parameters: materials, structures, terminals and deposition process. The matrix, shown in Table 2, summarizes multijunction research activities conducted by federal agencies and industry. Near-term and far-term expectations of the experts surveyed are shown in Table 3.

Table 2. Multijunction Technology Comparison, Matrix B

Organization	Materials	Structure	Terminals	Deposition	Accomplishments and Highlights
SERI ^a	GaAsP/ GaAs or Si	Monolithic	2	OMCVD	14% (1X), GaAs n+/i/p/p ⁺
Sandia ^a	AlGaAs, InGaAs	Monolithic	4, 3 or 2	MBE	MBE in operation
LeRC ^a	AlGaAs/ GaAs	Monolithic	2-4	OMCVD	OMCVD in operation
Chevron	GaAsP/ GaAsSb	Monolithic, back-to-back	3	Vac OMCVD	22%, GaAsP on GaAsSb (1 sun). Initiated Mg doping. GaAsP cell, 17% at 130X
Hughes	AlGaAs/Si	Mechanical Stack	4	LPE	22% (100X), GaAs/ Si mech. stack
	AlGaAs/GaAs	Monolithic	2 or 3	LPE	>23% (100X), AlGaAs/GaAs heteroface
MIT/LL	AlGaAs or GaAsP/Si	Mechanical Stack	2 or 4	OMCVD	20% CLEFT on Si AlGaAs 16.9%, 1.8 eV GaAsP 15%, 1.8 eV
RTI	AlGaAs/GaAs	Monolithic	2	OMCVD	16% (without AR), AlGaAs/GaAs, two-junction
Spire	AlGaAs or GaAsP/Si	Monolithic	2	OMCVD	20.5% (1X), AlGaAs/GaAs heteroface
	AlGaAs/Si	Mechanical Stack	4	OMCVD	
Varian	GaAsP/ GaInAs	Monolithic	2	OMCVD	24% at 400X, AlGaAs/GaAs heteroface
	AlGaAs/ GaInAs				22% at 130X (AM0), AlGaAs/GaAs MIC ²
	AlGaAs/Si	Mechanical Stack	4	OMCVD	
ASEC	GaAs	Single- junction	2	OMCVD	16.9% (AM0) 2 x 2 cm AlGaAs cell

^aIn-house

Table 3. Multijunction Technology Expectations

Time	Materials	Structure	Terminal	Deposition	Accomplishments Highlights
Near-Term	AlGaAs and Si tech.	Mechanical stack	4	OMCVD LPE	25% multijunction cell
Far-Term	Advanced III-V materials	Superlattice tunnel-junction monolithic structures	2	High-quality film deposition	30% (at 100X), two-terminal MJ

SECTION IV

REQUIREMENTS AND APPROACHES

This section reviews the requirements for multijunction cell structures and materials to increase conversion efficiency significantly, and analyzes the approaches being used to predict the potentials for multijunction cells to optimize their efficiency.

A. CELL STRUCTURES

Multijunction cell structures have the potential to achieve high efficiencies by stacking one or more cells to make better use of the solar spectrum. Several studies conducted on theoretical efficiencies of multijunction cells indicate that the efficiency can, in principle, be increased to greater than 55% with about 10 to 20 junctions of different materials stacked upon one another. In practice, however, developing such structures is difficult and a maximum of two or three subcell stacks is considered feasible to achieve an optimum high-efficiency device. Table 4 shows the possible theoretical efficiency for single-junction, two-subcell-stack and three-subcell-stack material systems for concentrator modules. This table also shows the optimum band gaps for each cell. Figure 1 shows the range of band gaps for top and bottom cells to achieve the efficiencies indicated. It can be concluded that band-gap selection is not critical for a four-terminal device, but for two-terminal devices the current-matching requirement is a primary driver. Many combinations of materials are possible that will meet the multijunction cell efficiency requirements; however, quality and compatibility of materials are critical. To build successful multijunction cells with high efficiency, it will be necessary for each subcell in the stack to produce high-efficiency performance.

Multijunction cell structures can be grouped into three categories, depending upon methods for the structural integration of subcells: (1) spectrum splitter, (2) mechanical stack, and (3) monolithic structures. Cell structures, with specific examples, are listed below:

- (1) Spectrum-Splitter Cells
 - (a) Dichroic mirror, with physically separated high and low band-gap cells.
 - (b) High-energy gap (E_g) cell with back reflector, with physically separated high and low band-gap cells.
- (2) Mechanically Stacked Cells
 - (a) AlGaAs/optical adhesive/Si, four-terminal.
 - (b) GaAsP/optical adhesive/Si, four-terminal.

Table 4. Theoretical Efficiency of Concentrator Cells

	Optimal Bandgap(s) (Top to Bottom)	Theoretical Efficiency at 28°C, %
Single-Junction Cell (500X)	1.45 eV	32
Two-Cell Stack (500X)	1.6 - 0.95 eV	40
Three-Cell Stack (500X)	2.0 - 1.5 0.95 eV	47

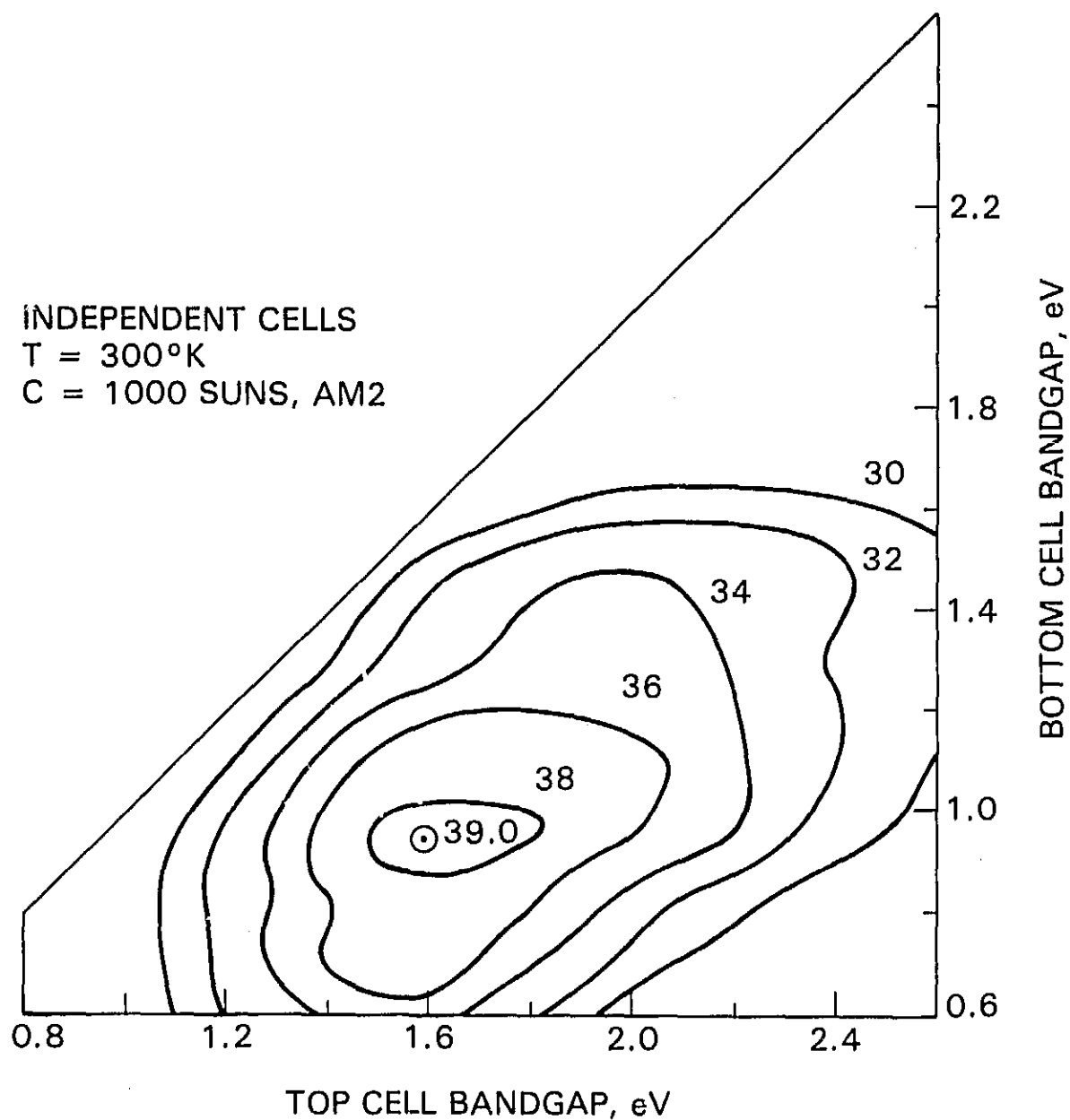


Figure 1. Two-Junction Photovoltaic Converter Iso-Efficiency Lines

(3) Monolithic Cells

- (a) AlGaAs or GaAsP/buffer or lattice constant matching graded layer/Si, two-terminal.
- (b) GaAsP/matching layers/GaAsSb, three-terminal.
- (c) AlGaAs/matching layers/GaInAs, two-terminal.
- (d) AlGaAs/matching layers/GaAs, two-terminal.
- (e) AlGaAs/superlattice/InGaAs, two-terminal.

1. Spectrum-Splitter Cells

Early spectrum-splitter cells consisted of a dichroic mirror that transmitted short and long wavelength components of the solar spectrum to a high-energy-band-gap (E_g) AlGaAs cell and to a low-energy-band-gap silicon cell (Figure 2). The dichroic-mirror spectrum-splitter concept using an AlGaAs/Si combination was fabricated in 1983 by Varian for Sandia and demonstrated a 20% module efficiency at 477X. The combined peak efficiency of the AlGaAs and silicon cell with dichroic filter was 25% at 113X. This spectrum-splitter module has clearly demonstrated the high efficiency potential with the use of multiple-band-gap cells. The efficiencies measured are still the highest achieved by any multiple-cell configuration. This concept was subsequently superseded by a high-band-gap cell with a back reflector configuration. In this case, the dichroic mirror was replaced by a high-band-gap cell, with a reflective back surface so that the cell functions both as an optical filter and as a mirror. Reflected long-wavelength components of the solar spectrum are absorbed by a low-band-gap cell in this configuration. A high-band-gap back-reflector cell using a thin AlGaAs cell with a silicon cell achieved an efficiency near 20% at 21X.

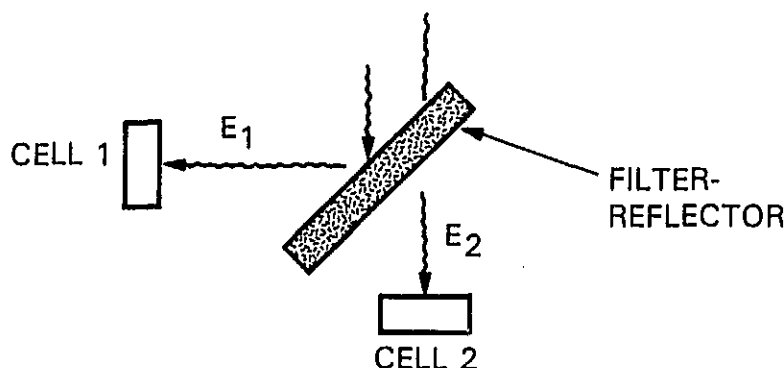


Figure 2. Spectrum-Splitting Schemes

2. Mechanically Stacked Cells

Mechanically stacked cells consist of multiple subcells, typically two, that are mechanically bonded together by an optically transparent adhesive such as an RTV. In this configuration, subcells may not require crystallographic match, and can be fabricated independently. Electrical output from each of the subcells is brought out separately so that the cells can be connected externally in series or parallel. In principle, then, current match is not required with mechanically stacked cells.

Mechanically stacked cells currently being developed consist of a high-band-gap III-V compound such as AlGaAs or GaAsP bonded onto a low-band-gap silicon cell. Acceptable III-V compound cells and silicon cells have already been developed. Recently (June 1984) an efficiency of 15.5% for thin GaAs and $\approx 18\%$ for a non-thinned GaAs cell at 1X was reported ($E_g = 1.65$ eV). Silicon-cell efficiency is now near 21% at concentrations exceeding 100X after many years of development. Although only a small number of mechanically stacked cells have been fabricated to date, a mechanically stacked Hughes GaAs/Si cell has already demonstrated an efficiency of 22% at 100X without any optimization of either cell for this configuration (Reference 1). Recently a series of experiments to simulate a mechanically stacked multijunction solar cell were completed at Sandia. GaAs or AlGaAs cells were stacked on top of a silicon cell and the spectral response and I-V characteristics of the cell were measured at one sun and under concentrated illumination (up to 1000X). The stacks were bonded with GE RTV 615A; the GaAs and AlGaAs samples had AR coatings on both sides. Hence, the final structure was the same as that of a mechanically stacked cell except that the top cell did not have grid lines. Experimental results agreed very closely with predictions. Important conclusions of the experiment are: (1) optical coupling between the AlGaAs and silicon cells can be made very good (absorption losses were around 2.5% and reflectance losses could be made less than 7% with optimized AR coatings); (2) red-enhanced silicon cells can lead to a performance improvement of about 7% over more conventional silicon cells, and (3) the AlGaAs cell should have a bandgap larger than 1.67 eV to match the currents between it and the red-enhanced silicon cell. A 25%-efficient mechanically stacked cell is considered to be feasible if available technologies are optimized.

3. Monolithic Cells

Monolithic multijunction cells are fabricated by sequentially growing component subcells having different band-gap energies. Inasmuch as materials having different band-gap energies are likely to have different crystallographic structures, each cell material must be structurally joined, using matching layers. These matching layers can be graded layers, superlattice structures or relatively simple buffer layers. Additionally, each cell must be electrically connected, preferably in series, so that the resultant cell assembly has only two terminals. Therefore a two-terminal, monolithic multijunction cell requires ohmic interconnect regions between subcells. The ohmic interconnect can be a tunnel junction and/or a dislocation pile-up region such as in the AlGaAs/Si cell fabricated by MIT-LL. Each subcell must generate the same current, at least at a particular air-mass condition, for the two-terminal multijunction cell to perform efficiently. The current match problem may be eliminated by providing

separate output terminals for each subcell such as are used in the back-to-back, GaAsP/GaAsSb, three-terminal cell device shown in Figure 3. A pn/np three-terminal cell fabricated by Chevron achieved a 1-sun efficiency of 22%. An extension of the three-terminal type structure to multijunction cells having more than two subcells has not been attempted and would be impractical. The three-terminal multijunction cell is an alternative to the mechanically stacked approach to achieve a near-term efficiency of 25%.

The AlGaAs/GaInAs cell shown in Figure 4 uses graded window layers between top and bottom cells for structural match, and a metal interconnect for electrical contact. A similar cell, but with GaAs for the bottom cell, was fabricated by Varian, and it has achieved a conversion efficiency of 22% at 130X, AM3. An improved MIC² cell is currently being developed for SERI

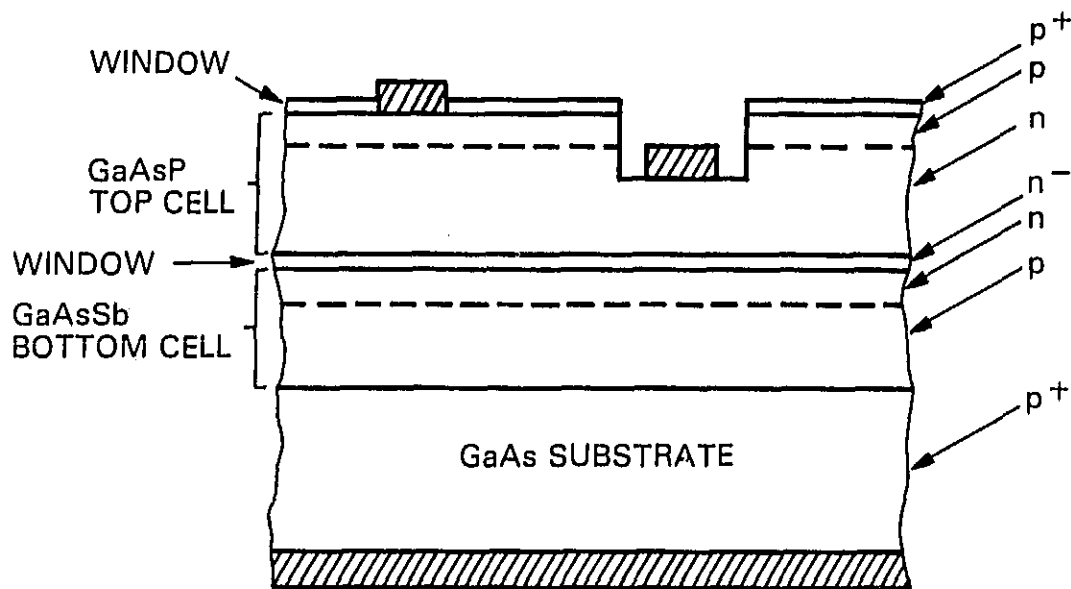


Figure 3. Two-Color Three-Terminal Solar Cell (Chevron)

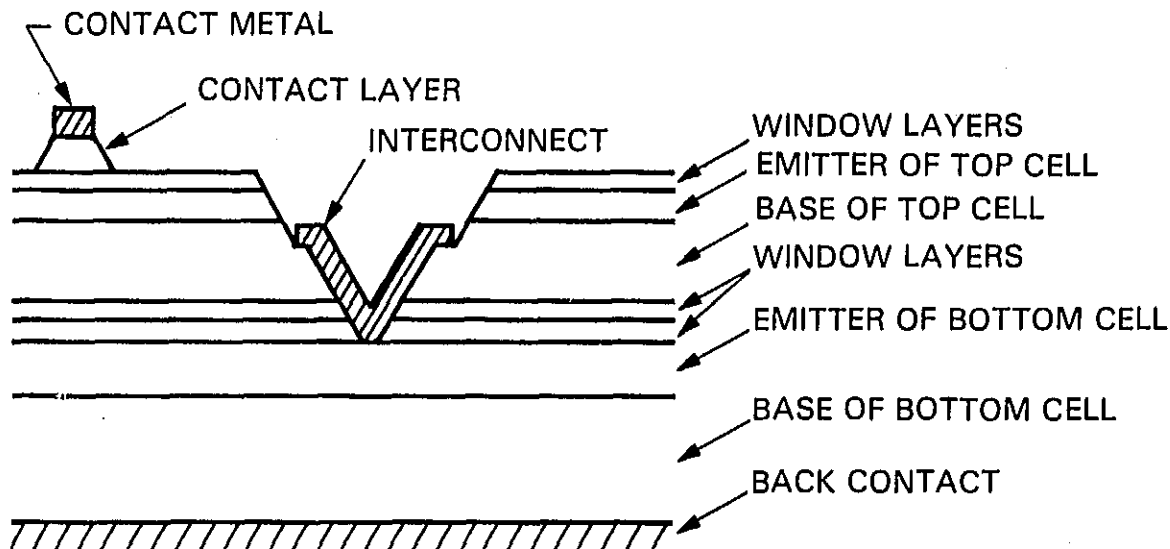


Figure 4. Metal-Interconnected Cascade Cell (MIC²) (Varian)

using an AlGaAs/GaInAs or GaAsP/GaInAs combination. The projected efficiency of the AlGaAs/GaInAs, MIC^2 cell is 28.3% at 100X.

A monolithic GaAsP/Si cell being developed by SERI is grown by the OMCVD process. The GaAsP cell (1.7 eV) will be grown on a silicon cell by first growing a thin GaP layer. GaP has a good lattice match to silicon. The lattice constant is then graded to the GaAsP cell by a superlattice. An electrical connection between the top and bottom cell is formed by a heavily doped GaAsP tunnel junction. Dislocations originating in the tunnel junction are terminated within a few layers of superlattice adjacent to the junction, thus leaving the top cell junction free of damaging dislocations. Researchers at Varian and SERI are using strained-layer superlattice (SLS) as an interconnection layer between the low and high band-gap cells and are exploiting the ability of SLS to terminate propagation dislocations. At Sandia, a SLS is being examined for active regions exploiting the ability to tune the band gap of SLS independent of the lattice constant. Initial efforts are examining SLS materials consisting of alternating layers of AlGaAs and InGaAs grown by molecular beam epitaxy (MBE).

An effect has been found that has a strong influence on the morphological stability of OMCVD-grown $\text{GaAs}_{1-x}\text{P}_x$ superlattices. Under conditions that normally produce distorted layers at a growth rate of $0.04 \mu\text{m}/\text{min}$, increasing the growth rate to $0.12 \text{ m}/\text{min}$ eliminates virtually all of the distortion. The growth temperature has also been found to play a significant role, with lower temperatures producing the better layers. These effects are in addition to the previously reported effects of interlayer strain and buffer layer grading, so that optimization of a combination of these effects can now practically guarantee a distortion-free superlattice.

As suggested in the above analysis, monolithic multijunction cell structures have various advantages over other structures with respect to their possible simplicity of electric output arrangements, requiring only two terminals; relative simplicity of fabrication process, and potentially higher conversion efficiencies. To realize the above advantages, however, the following are needed: (1) sophisticated deposition processes involving OMCVD or MBE at high yields, (2) the deposited layers must be of high quality, free of damaging impurities and undesirable crystallographic defects and (3) low-loss interconnects between subcells must be perfected. Present technology for fabricating tunnel junctions is limited to a class of materials that may not be compatible with the materials used in subcells.

B. CELL MATERIALS

Cell materials for multijunction cells are required to have selected band-gap energies such that the solar spectrum can be divided into multiple-wavelength regions. Each cell material, having an appropriate band gap, can convert a segment of the solar spectrum to electrical energy efficiently. The constraint in material selection that is especially important for monolithic multijunction cells is that the lattice parameters must match closely enough not to cause undesirable distortions and dislocations.

Candidate III-V materials having band-gaps and lattice parameters that could satisfy the above conditions are shown in Figure 5 (Reference 1). The

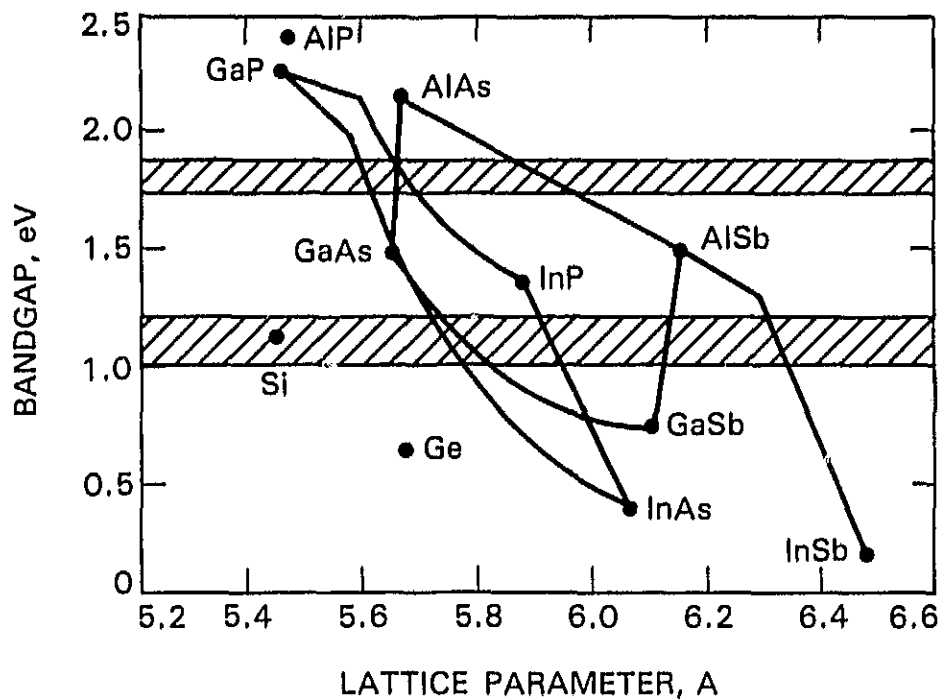


Figure 5. Band-gap Energies and Lattice Constants for selected III-V Compound and Elemental Semiconductors

subcell materials must be selected so that the output currents from the subcells match closely. This is especially important with series-connected monolithic cells. This constraint is less important with three-terminal or four-terminal multijunction cells.

SECTION V

RESEARCH NEEDS FOR MULTIJUNCTION CONCENTRATOR CELLS

The research requirements for multijunction concentrator cells can be organized into four areas. First, there is a continued need to improve the quality and understanding of the ternary and quaternary III-V compounds. This is the primary emphasis of the SERI program. Second, the fundamentals of the crystal-growth process require considerable study to provide precision, control, and reproducibility. This will provide industry with the foundation needed for engineering research to establish production facilities. Third, to provide the tools needed to optimize the design of the solar cells, research must be directed toward the materials, components, and measurements of high-efficiency cells; e.g., tunnel junctions, metallizations, optical coatings, and characterization of parameters needed in cell performance modeling. The final area of research combines the results of the other three areas in a focused effort to demonstrate, reproducibly, optimum solar-cell structures. More detail on these areas of research is provided in the following subsections.

In addressing the research needs, it is important to draw on the special skills of industry, university, and government laboratory research teams. For example, to study the effects of gas flows in OMCVD, the research will be meaningful only if the industry team selected for the project already can make state-of-the-art material. University research must be closely coupled to the work of the industry leaders, as in characterizing defects in state-of-the-art crystals grown in industry or government laboratories. The management of these coordinated projects will be an important challenge.

A. IMPROVED III-V ALLOYS

Two-cell tandem structures can achieve more than 30% efficiency under concentrated sunlight using existing planar junction cell designs. However, some further improvement in the quality of the semiconductors and the basic junction properties is still required. These improvements can be obtained through continued support of the research on ternary alloys for monolithic and stacked devices. Such research would focus on methods to control the location of misfit dislocations, control of dopants, minimization of incorporation of impurities, and fabrication of test structures. Additional basic experimental and theoretical analyses of the properties of these semiconductors are needed. This information will be important in achieving efficiencies higher than 30%.

1. Effects of Impurities and Defects

To approach theoretical maximum efficiencies of III-V solar cells, it is increasingly important to improve the understanding of the effects of impurities and defects on the electronic properties of binary, ternary, and quaternary crystals. This understanding can only be developed through a combined program of experimental and theoretical analysis. Currently, the

tools developed by theorists have been applied only to the binary compounds. Given the additional complexity of the alloys, a significant effort will be required to adapt the techniques to describe adequately the interactions of an impurity or other defect with the host lattice. The theory is of little value unless it can be compared with the experimental results. Techniques such as deep level transient spectroscopy (DLTS) have been applied to the study of GaAs and some compositions of the ternary alloys. However, the quality of crystals is improving so quickly, especially in the ternaries, that much of the existing data are no longer useful. Joint programs of research are needed to analyze current state-of-the-art materials.

2. Control of Dopants and Defects

Defects are a natural part of the crystal in a lattice mismatched structure. However, if the location of the defects can be controlled so that they occur only in the inactive regions of the device, they will not affect the performance of the solar cells adversely. It is known that the propagation of defects can be modified through control of strain in the crystal structure. Continued research to maximize this control is critical for improvements in cell efficiencies.

Improved control of the doping concentration and profile of doped regions is also needed to achieve optimum efficiencies. This requires study of the crystal-growth process to minimize the memory effects caused by dopants adsorbed on reactor and gas-line surfaces. The problem of diffusion of dopants during growth also must be solved. To reduce series resistance to levels acceptable for operation at high concentration levels, it may be appropriate to initiate research on non-equilibrium techniques to obtain higher doping levels without greatly affecting V_{oc} .

3. New Materials, Such as Quaternary Compounds

The current state of the art in III-V semiconductors limits the selection of materials for the top and bottom cells of a cascade structure. Candidates for the top cell are AlGaAs and GaAsP. Useful performance has been obtained in GaInAs, GaAsSb, and silicon bottom cells. Continued improvements may permit a return to the study of quaternary compounds for active cells. Quaternaries offer the advantage of allowing selection of both optimum cell bandgap and lattice constant adjustment to obtain a lattice matched multilayer structure.

B. CRYSTAL GROWTH PROCESSES

Use of the OMCVD process allows considerable flexibility in growing the complex crystal structures of multijunction solar cells. The best samples obtained to date are of sufficient quality to potentially allow achievement of more than 30% efficiency. However, the process parameters used on the research-sized reactors have been established empirically. There are fundamental questions regarding the reaction chemistry, gas dynamics, source impurities, and other aspects such as memory effects that must be answered.

The efforts to scale up this growth process have encountered severe difficulties due to the lack of understanding of these factors. The attempted scale-up, performed with USAF funding, has also been by an empirical approach. This presents an unacceptable level of risk for industry to undertake without federal support. Research on the crystal-growth processes is needed to improve the reproducibility of laboratory results as well as to develop the analytical tools needed for design of predictable production units with acceptable yields.

1. Reaction Chemistry

At present most OMCVD growth is accomplished through the reaction of trimethylgallium (TMG) or trimethylaluminum (TMA) with arsine. There is recent evidence that other organo-metallic sources, such as triethylgallium and trimethylarsenic, may yield superior crystals. To date only a very limited amount of research has addressed the use of alternate source materials. The mechanisms of the TMG/arsine reaction and formation of gaseous by-products are not well characterized. Failure to understand this reaction fully can lead to incorporation of carbon and other impurities into the crystals.

2. Gas Dynamics

It is not now possible to design a large-scale OMCVD reactor analytically. Current efforts to develop a volume manufacturing technology for gallium arsenide solar cells are plagued by problems that require continuing experimental redesign of the reactor. Obtaining uniform films in a large reactor presents a major problem. Undoubtedly this arises largely from a non-uniform flow of reactant gases over the susceptor. Even if the flow were uniform, there still may be problems of depletion of the concentration of source material in the flow. Research is required to establish the analytical tools needed by production engineers to develop viable production processes.

3. Source Purity

The quality of organo-metallic sources for growth and doping is improving. This is evident in the quality of crystal that can now be grown. However, batch-to-batch uniformity of the sources presents a significant problem for research and will cause severe problems in production. At present, the leading teams must repurify many of their source materials. Even then the reactor must be recharacterized each time a source is replaced. These problems cause delays in research, but, more important, add a level of confusion to the results. An effective program in source purity was carried out in 1980. The SERI subcontractor interacted effectively with the vendor to improve source quality. A renewed effort in this area would provide significant benefits for the entire III-V community.

C. COMPONENTS OF HIGH-EFFICIENCY CELLS

As the quality of the active semiconductor layers improves, increasing emphasis will be needed in research on devices. To provide the device designers with the best tools to optimize cell performance, materials research will be needed to improve optical coatings, metallizations, cell interconnects, and tunnel junctions. At present, the III-V community does not have the same capabilities in device processing as have proved so valuable in high-efficiency silicon cells. These device processing and measurements technologies must be developed through research.

1. Antireflective Coatings

The overall purpose of the multijunction cells is to improve the response of solar cells over a wide spectral range. This goal places stringent requirements on the quality of antireflective coatings. A single-layer coating tuned to the peak response may be sufficient for a single-junction cell. Two-layer or three-layer coatings will likely be required for multijunction cells.

2. Interconnects

Operation under high concentration requires optimum metallization and interconnection between top and bottom cells. The research recently initiated by Sandia must be continued to meet these needs. The problem of interconnecting monolithic cells also requires study. The current approach using metallized etched grooves can provide a baseline technology. In future production, interconnection using a tunnel junction or other crystalline contact would provide advantages in cost and yield.

D. OPTIMUM-CELL RESEARCH

Having established an improved quality of the active semiconductors, as well as the necessary components of the high-efficiency cell structures, the technology would embark on a solar-cell research program similar to current efforts in high-efficiency silicon cells. Research on optimizing the performance of single-junction GaAs cells has recently begun. Using device models with accurately measured materials parameters, improved cell structures could be designed and tested. The community would then be prepared to address the more complex ternary alloys and multijunction structures.

SECTION VI

CONCLUSIONS

The PA&I study team, with the assistance of SERI and Sandia team members, have reviewed the collected data on multijunction cells for concentrators and, based on the opinions and comments of the researchers interviewed, and on the assumption that adequate funding will continue, have arrived at the following summary statements:

- (1) Higher than 25% efficiency in multijunction cells may be achieved soon at moderate concentrations; when these cells are optimized, they could achieve 30% efficiency.
- (2) Multijunction cells of 30% efficiency for concentrators may be achieved within two years, probably with a three-terminal or four-terminal configuration.
- (3) Multijunction cells of 35% efficiency for concentrators are still quite far off; they are probably not achievable until the late 1980s or early 1990s and will require innovation (e.g., a unique structure with near-ideal materials and possibly three junctions).
- (4) III-V material quality is expected to be the key to success for monolithic cells. Continued and expanded material research and research on impurity effects is needed.
- (5) Difficulties have been experienced by researchers in fabricating good tunnel junctions. According to some experts, III-V materials tunnel-junction formation will require further technology advancement to achieve increased doping concentration to as high as 10^{19} . There are also some concerns that the series resistance of a tunnel junction is too large for high concentration (500X) use.
- (6) Source-material purity problems still hinder the assessment of the growth chemistry.
- (7) Measurement standards and measurement procedures for multijunction devices are badly needed to allow uniform comparative performance evaluations.
- (8) The OMCVD process is presently considered to be the best low cost process for mass production of multijunction cells. Liquid-phase epitaxy (LPE), although less flexible than OMCVD, and therefore less suitable, has been used successfully to produce high-efficiency GaAs cells with good yield, and is still a viable option for multijunction concentrator cells.

To achieve the objectives and goals of the National Photovoltaics Program for multijunction cells for concentrators, the team members identified the

following key areas of research needs for achievement of in high-efficiency cells:

- (1) Improved quality and understanding of ternary and quaternary III-V compounds.
- (2) Precision control of crystal growth processes.
- (3) Research in materials, components, and measurement techniques and standards.
- (4) Device research involving modeling, advanced measurements (lifetimes, recombination current, etc.) and processing to optimize the solar cell for each III-V alloy.

These key research areas require a multidisciplinary team that includes industry, university and DOE Field Center experimenters. Specific research tasks that require further development are listed, not in order of priority:

- (1) Materials research to establish purity and crystalline defect limit requirements.
- (2) Assessment of the electronic effects of materials impurities and defects.
- (3) Research on source-material purity requirements.
- (4) Assessment of the effects of dopant diffusion and complexing with other impurities and crystalline defects.
- (5) Development of low-loss tunnel junctions or other appropriate ohmic contacts between monolithically stacked p-n junctions.
- (6) Research on reaction chemistry during OMCVD growth.
- (7) Research to provide the analytic tools needed to scale up crystal growth processes for quantity cell production with acceptable yields.
- (8) Development of satisfactory lattice matching interlayers to minimize crystalline imperfection.
- (9) Fabrication of monolithic heterostructures, using materials not matched in lattice constants.
- (10) Development of measurements for accurate comparative performance evaluation and for device characterization.
- (11) Development of modeling capability for single-junction and multijunction devices.
- (12) Research on device processing, e.g., multilayer optical coatings, metallization, and cell interconnects.

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2. Fan, J.C.C., Tsaur, B.Y., and Palm, J., SPIE-Photovoltaics for Solar Energy Applications II, Vol. 407, pp. 73-87, 1983.

APPENDIX A
INDUSTRY SURVEY DATA

Industry surveys were conducted to review the status of multijunction technology. The organizations visited are either conducting research on multijunction devices for concentrators or are involved in research related to multijunction cell technology. Those surveyed:

Hughes Research Laboratories, Malibu, California
Chevron Research Laboratories, Richmond, California
Varian Associates, Palo Alto, California
Research Triangle Institute, North Carolina
MIT Lincoln Laboratories, Boston, Massachusetts
Spire Corp., Bedford, Massachusetts
Applied Solar Energy Corp., City of Industry, California
Rockwell International, Thousand Oaks, California

Objectives were (1) to determine multijunction technology research status, (2) to obtain industry projections for the multijunction cell technology development time scale, and (3) to obtain industry opinions regarding the achievement of the DOE objectives and goals.

A. HUGHES RESEARCH LABORATORIES, MALIBU, CALIFORNIA

Information obtained from discussions with Hughes researchers on January 19, 1984, and from SERI publications of contractor reviews is summarized below. Sanjiv Kamath, Section Head; R.C. Knechtli, Senior Scientist; and R. Loo, Member of the Technical Staff, were interviewed.

Project sponsors for the work are the U.S. Air Force and Sandia. Work is being done for Sandia on an AlGaAs/Si mechanical-stack, four-terminal multijunction cell and for the USAF on an AlGaAs/GaAs monolithic two-junction cell.

Progress on this research is described:

- (1) Eighty single-junction AlGaAs/GaAs heteroface cells (2 x 2 cm) can be produced per run with good yield by pilot production LPE machines.
- (2) AlGaAs/GaAs single-junction concentrator cells (0.5 cm diameter) made for LeRC achieved >23% efficiency at 100X, AM1 (Sandia measurement of 25% later corrected downward).

- (3) Good ohmic contact was achieved using a Au-Zn combination on AlGaAs.
- (4) Precise etching has been developed for thin-film device fabrication.
- (5) Other needed microelectronic-related processing technologies are on hand at Hughes.
- (6) The LPE single-junction manufacturing technology will be transferred to Hughes' Spectrolab subsidiary.

Plans for this work include achievement of 25% AMO efficiency with a monolithic multijunction cell for the Air Force and a thin AlGaAs top cell for Sandia.

The following additional comments were offered regarding multijunction cell technology:

- (1) Thin AlGaAs top cell fabrication on a sacrificial substrate should be achieved in 1984.
- (2) Difficulties in fabricating good tunnel junctions required for two-terminal multijunction cells are stressed by Hughes (Kamath) with the observation that alternative interconnect schemes are available and are likely to be used by Hughes.
- (3) Two-terminal or four-terminal 25%-efficient AMI monolithic cells are feasible in 1984.
- (4) Two-terminal 30%-efficient AMI, multijunction cells are still a couple of years away, and achievement of 35% is several years beyond that.
- (5) The effects of material impurities are not well understood and present a major problem. More research funding is needed in this area.
- (6) Performance measurement and efficiency comparisons of thin-film devices for multijunction cells have been a problem because of the lack of standard measurement procedures and instrumentation.

B. CHEVRON RESEARCH LABORATORY, RICHMOND, CALIFORNIA

Information obtained from discussions with Chevron Research Laboratory researchers on January 24, 1984, and from SERI publications of contractor reviews is summarized below. The persons contacted were John Cape, L. Fraas, and P. McCloud. A new contract exists with SERI and one is being negotiated with USAF; these are in addition to in-house-funded projects. Work under way involves GaAsP/GaAsSb, two-junction three-terminal devices using two GaAs transition layers, with a pn-np structure. Progress on this work is described as follows:

- (1) A vacuum OMCVD system has been in operation for some time. It produces films of high uniformity with efficient use of source material.

- (2) A monolithic GaAsP on GaAsSb cell achieved 22% efficiency using Zn p dopant; top-cell-18.3%, bottom-cell-3.6%. Mg doping is expected to improve the efficiency of bottom cell to 6.5%.
- (3) Mg p dopant is being investigated for use in place of Zn dopant to increase the p-doping concentration of the GaAsP layers with the increased phosphorus incorporation. Mg doping also eliminates the unwanted Zn diffusion and Zn "memory" effects.
- (4) Purification of the organo-metallic Mg source material is necessary before its use.
- (5) GaAsP (1.65 eV) cells have been fabricated with 17% efficiency at 130X.

Plans include achieving near-term efficiency of 25% for GaAsP on GaAsSb by improving top-cell (GaAsP) performance. This will be accomplished by using an Mg dopant and surface optimization, and by improving the bottom cell (GaAsSb) through use of better source materials (tri-ethyl antimony and Mg-dopant).

J. Cape offered the following comments on multijunction cell technology:

- (1) A back-to-back, three-terminal device is easier to fabricate than a true superlattice, tunnel-junction-interconnected device.
- (2) Lattice mismatch up to 1.5% may not impair two-junction cell performance.
- (3) Purification of source material is important. Purification of both Zn and Mg is ongoing at the Chevron facilities.
- (4) The extent of impurity effects on cell performance has not been well documented for each impurity species.
- (5) Reaction chemistry for materials such as tri-ethyl antimony and biscyclopentadienyl-magnesium (CP_2 -Mg) requires further investigation.
- (6) There is difficulty in measuring performance of devices because no standard cell or measurement approach exists.

C. VARIAN ASSOCIATES, PALO ALTO, CALIFORNIA

Information obtained from discussions with Varian Associates researchers on January 25, 1984, and from SERI publications of contractor reviews is summarized below. The persons visited were Ron Bell, Project Manager; Jan Werthen, and Carol Lewis. The work is performed under the sponsorship of Sandia, NASA, USAF, and SERI. Focus is upon III-V ternary compounds used in conjunction with a strained-layer superlattice interlayer and MIC^2 interconnect techniques. Varian has also used graded III-V quaternary materials as interlayers. Candidate top cells are GaInP, GaAsP, and AlGaAs; the candidate bottom cell is GaInAs. Both cells are grown by OMCVD. A thin

AlGaAs cell is also being developed for Sandia for use in mechanically stacked structures.

A progress summary:

- (1) Extensive experience exists using OMCVD technology for thin-film growth of III-V compounds, with excellent uniformity of deposition and reproducibility of growth.
- (2) AlGaAs/GaAs single-junction heteroface concentrator cells made for Sandia have demonstrated 24% efficiency at 400X. Two cells measured at SERI were reported to have efficiency greater than 20% at 1 sun. Each had a band gap of 1.64 eV, near the optimum for the top cell of AlGaAs/GaInAs multijunction cells. One cell has an area of 4 cm².
- (3) Linear and step grading techniques have proven successful.
- (4) Internal quantum efficiencies of various combinations of III-V ternaries have been measured.
- (5) An AlGaInAs quaternary-graded layer was developed for subcell layers in tandem III-V ternary cells.
- (6) Mask sets that are optimized for 40 suns for Metal-Interconnected Cascade Cell (MIC²) interconnects have been fabricated.
- (7) Mg has been shown to be the preferred p dopant. In OMCVD, Zn diffuses too rapidly during growth of the top cell, and the diffusion degrades the high efficiency of the bottom cell. Mg dopant has not exhibited this problem.

Plans for work at Varian include:

- (1) Testing of AlGaAs/InGaAs cells with MIC² technology, which should begin in May or June 1984.
- (2) Further development of GaAsP cell material, and if appropriate, its substitution for the AlGaAs top cell.
- (3) Fabrication of thin AlGaAs films for use in mechanically stacked multijunction cells.

The following additional comments were made:

- (1) Strained layer superlattice requires further development to provide lattice match and internal contact.
- (2) Mechanically stacked multijunction cells, 25% efficient at concentration, appear achievable in the near term.
- (3) Materials purity is of great concern; Varian is purifying incoming materials.

- (4) A 30%-efficient multijunction cell is expected to be available by 1985, with 35% efficiency at least five years away.

D. RESEARCH TRIANGLE INSTITUTE, RESEARCH TRIANGLE PARK, NORTH CAROLINA

Information obtained from discussions with Research Triangle Institute (RTI) personnel on March 1, 1984, and from SERI publications of contractor reviews is summarized. The persons visited were Jim Hutcheby and Mike LaMorte. Project sponsors are SERI and the USAF. The work involves AlGaAs/GaAs graded band-gap, monolithic, two-terminal cells, patterned Ge tunnel junctions, and OMCVD.

Progress at RTI is summarized:

- (1) Epitaxial growth of AlGaAs/GaAs has already been demonstrated.
- (2) Conformal epitaxial growth of AlGaAs on patterned Ge stripes has also been demonstrated.
- (3) Computer analysis of a practical AlGaAs/GaAs cell structure, supported by USAF, indicated that one-sun efficiency of 25%, AM1.5 (experimental efficiency was 16% without AR); and 500-sun efficiency of 30%, AM1.5 are achievable.
- (4) Under a previous SERI contract, AlGaAsSb/GaAsSb cascade cells have been fabricated using LPE.
- (5) Mg was found superior to Be as a dopant.
- (6) A GaAsSb tunnel junction achieved 10 amp/cm² peak current.

Plans are centered on the following items:

- (1) Demonstration of epitaxial growth of a new AlGaAs layer on oxidized AlGaAs. To fabricate a patterned Ge tunnel junction on AlGaAs in the RTI equipment, the film must be exposed to ambient between process steps.
- (2) Demonstration of low-resistance, patterned Ge tunnel-junction formation.
- (3) OMCVD growth of graded p-AlGaAs and p-GaAs layers to increase current collection.
- (4) OMVPE growth of low-carbon, high-mobility GaAs by purification of the trimethyl gallium source.

Those interviewed offered the following comments regarding multijunction cell technology:

- (1) Epitaxial growth of AlGaAs on oxidized AlGaAs is a new technology.
- (2) The interconnecting tunnel junction pattern must register with the top metallization.

- (3) Lattice match is important for achieving low dislocation density ($<1000/\text{cm}^2$) and good thermal stability.
- (4) A greater level of material research is needed to achieve good III-V solar cells.
- (5) Measurement standards are needed for thin-film multijunction devices.
- (6) 30% AM1 efficiency multijunction cells can be expected within a couple of years; 35%-efficient cells are at least five years away.

E. MASSACHUSETTS INSTITUTE OF TECHNOLOGY LINCOLN LABORATORY,
BOSTON, MASSACHUSETTS

The information obtained from discussions with Massachusetts Institute of Technology Lincoln Laboratory (MIT-LL) researchers on March 2, 1984, and from SERI publication of contractors reviews is summarized below. John Fan of MIT-LL was interviewed. Project sponsors for this work are SERI, USAF, and NASA. The work centered upon AlGaAs/Si or GaAsP/Si cells grown with OMCVD and a CLEFT-grown AlGaAs top cell for mechanically stacked cells.

Progress is described as follows:

- (1) CLEFT technology is being developed for AlGaAs, GaAs, and GaAsP.
- (2) One-sun efficiency at 16.9% AM1 has been demonstrated with $\text{Al}_{0.2}\text{Ga}_{0.8}$ as shallow homojunction cell.
- (3) A 15% AM1 efficiency has been demonstrated with a $\text{GaAs}_{0.75}\text{P}_{0.25}$ cell.
- (4) 20% efficiency has been achieved with a GaAs/Si mechanically stacked cell.
- (5) GaAs has been grown epitaxially on Si.
- (6) Defect densities on heteroepitaxial GaAs on silicon have been reduced to $10^4/\text{cm}^2$.

Plans include:

- (1) Reduction of dislocation density in GaAs that is grown epitaxially on Ge/Si.
- (2) Improvement of AlGaAs and GaAsP material quality.
- (3) Epitaxial growth of AlGaAs or GaAsP on Si or Ge/Si.

J. Fan offered the following comments regarding multijunction cell technology:

- (1) The tunnel-junction cell interconnect approach is difficult.
- (2) For multijunction cells, three junctions are the upper practical limit.
- (3) Research priority should continue to be for devices, with moderate increase in funding recommended. Significant increase is recommended for materials R&D if any III-V funding increase occurs.
- (4) Four-terminal 30%-efficient AM1 multijunction cells are feasible in the near future; 35% multijunction cells are at least a few years away.

F. SPIRE CORP., BEDFORD, MASSACHUSETTS

The information obtained from discussions with Spire researchers on March 7, 1984, and from SERI publications of contractors reviews is summarized below. The persons visited were Roger Little, Ghazi Darkazalli, Vic Dalal, Bob Wolfson, and Sam Rechteris. Work is under sponsorship of SERI and Sandia for AlGaAs, GaAsP, and GaAs on Si or Ge for two- or four-terminal structures using OMCVD.

Progress is summarized:

- (1) An OMCVD AlGaAs/GaAs cell on GaAs substrate achieved a one-sun AM1.5 efficiency of 20.5%, with 22% expected in the near future.
- (2) A GaAs cell on Ge substrate achieved 15% efficiency.
- (3) An ion-implanted single-crystal Si cell achieved one-sun AM1 efficiency of 18%.
- (4) Heteroepitaxial growth has been achieved for GaAs and AlGaAs directly on silicon and on germanium-coated silicon.
- (5) Spire is marketing a complete line of PV module production machines.

Plans include:

- (1) Further efficiency improvement of Si cell to 20%.
- (2) Delivery of a thin AlGaAs top cell with 17% efficiency (400X) to Sandia.
- (3) Development of 16%-efficient two- or three-junction amorphous-silicon solar cells in the near term.
- (4) Demonstration of a 24% to 26%-efficient tandem cell between 1986 and 1988 (one sun).

The persons interviewed offered these comments on multijunction cell technology:

- (1) Mechanically stacked cells of 25% efficiency will be achieved in three to four years.
- (2) Spire is also developing amorphous silicon multijunction cells for flat-plate applications.
- (3) Measurement of device performance is difficult because of lack of standard measurement procedures and instrumentation.

G. APPLIED SOLAR ENERGY CORP., CITY OF INDUSTRY, CALIFORNIA

The information obtained from discussions with Applied Solar Energy Corp. (ASEC) researchers on March 23, 1984, has been summarized below. The persons contacted were Ku Sun Ling and Peter Iles. The program is sponsored by USAF, LeRC and Sandia, and is aimed at a high-efficiency GaAs cell for flat-plate space PV arrays and a high-efficiency silicon concentrator cell.

Progress is summarized:

- (1) Silicon cell efficiencies higher than 20% (100X) have been demonstrated by optimizing cell surface properties, including AR coatings, passivation, and grid structures.
- (2) Efficiency of 16.9% (AM0), 20% (AM1) 1-sun has been demonstrated with 2 x 2-cm GaAs cells produced by an OMCVD process for USAF.
- (3) ASEC is capable of producing 1,000 2 x 4-cm AlGaAs/GaAs cells per week at present by OMCVD with a good mechanical yield (80%).

Plans include:

- (1) Improvement of silicon concentrator-cell efficiency for concentrations above 200X.
- (2) Development of a mechanically stacked AlGaAs/Si cell with in-house and contract funding.
- (3) AlGaAs/GaAs cell production to be increased to 5,000 cells per week for USAF.

The persons interviewed offered USAF these comments on multijunction cell and related technology:

- (1) ASEC has set a present priority for GaAs cell quantity production over cell efficiency. Mechanical yield is good with electrical yield somewhat lower.
- (2) Reduction of Ga and As source material cost is required to achieve economic viability for GaAs cells.

- (3) Source materials may become a problem. At a production rate of 5,000 cells per week, ASEC could be using the entire world supply capability for pure growth source materials; however, Ga availability is not considered a problem.
- (4) Bridgeman and Cz growth control of GaAs is inadequate to ensure a low dislocation density supply of polished wafers. ASEC believes that they need less than 5,000 dislocations per cm^2 and would ultimately like much lower dislocation counts. It is difficult now to get wafer shipments of less than 10,000 dislocation density.
- (6) Sumitomo of Japan recently produced high-quality GaAs by liquid-encapsulated Cz growth. Samples procured showed at least an order of magnitude lower etch pit count than is typical of commercially available GaAs wafers.

H. ROCKWELL INTERNATIONAL, THOUSAND OAKS, CALIFORNIA

The information obtained from discussions with Rockwell International researchers on January 19, 1984, is summarized below. Stanley Zehr was interviewed. Rockwell has no solar-cell work at the present, but is involved in other GaAs electronic device development.

Progress was described as follows:

- (1) Infrared sensors have been developed for DOD.
- (2) GaAs high-speed semiconductor devices are being developed.
- (3) GaAs lasers and detectors have been developed using OMCVD.
- (4) InP lasers and detectors are being developed using LPE.
- (5) During the past contract with SERI, fabrication of a stacked AlGaAs/AlGaSb cell, with laser bonding at the interface, was attempted. The efficiency goal was 30%, but the cell was never fully developed during the contract. Rockwell subsequently dropped the PV work altogether and has no specific plans for it.

Zehr offered these comments on multijunction technology:

- (1) Monolithic multijunction cells connected by tunnel junctions are difficult to fabricate.
- (2) Ge tunnel junctions are relatively easy to fabricate, but they tend to be optically active in the undesirable direction.
- (3) More advanced materials research is needed in III-V compounds.